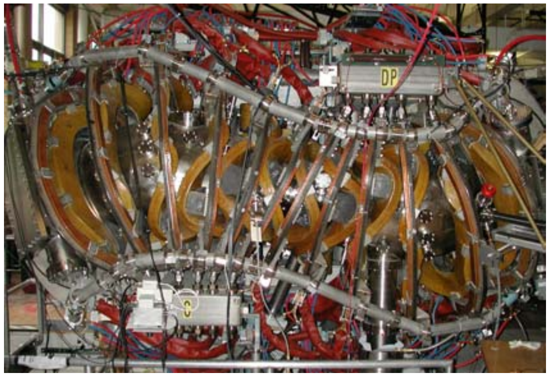
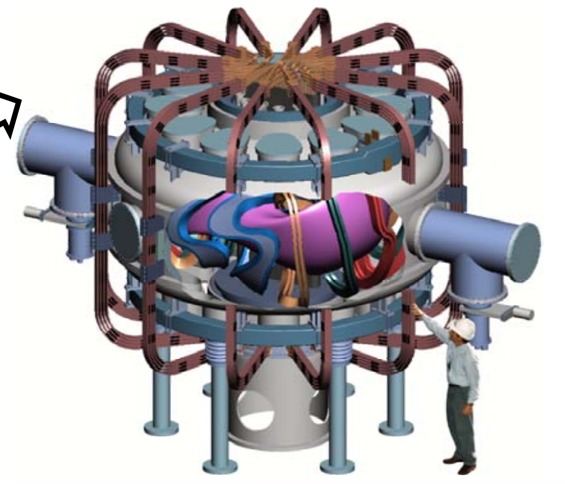
US Compact Stellarator *Program*

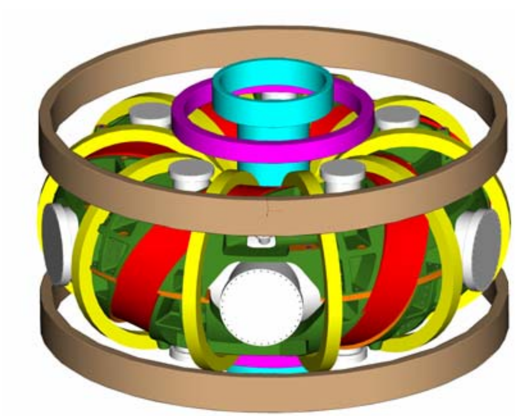


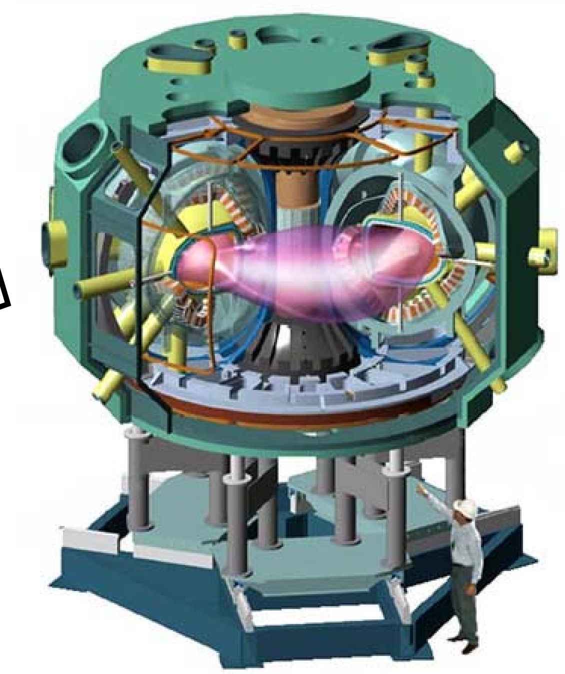


Theory and Modeling

3-D Plasma Science
Improved Understanding
of Toroidal Confinement
Benefits of 3-D Shaping

Improvements
in Toroidal
Fusion Reactor
Systems





D.T. Anderson, University of Wisconsin-Madison
for the US Stellarator Community

2005 Budget Planning Meeting
March 18, 2003

Why a Compact Stellarator Program?

- **The stellarator provides a solution to problems in toroidal confinement**
  - **Disruption elimination**
  - **Steady-state operation/No current drive needed; density limitations (W7AS ~ 3 x n_{gw} ; HDH mode)**

- **Two historical problems for conventional stellarators as reactors:**
  - **Neoclassical transport at low collisionality**
  - **Theoretically predicted stability β limits**

  → **High aspect ratio**

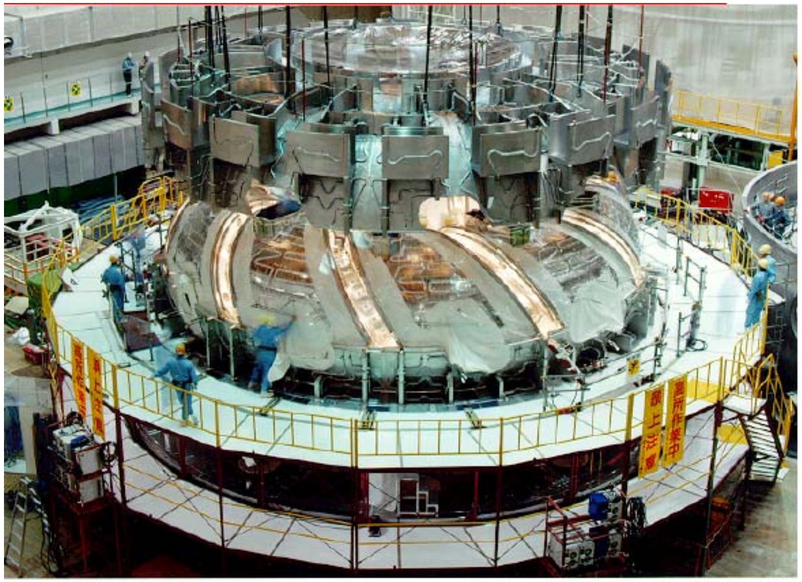
  Large size

- **The stellarator is a fully 3-D system; provides opportunities and challenges for basic science and toroidal confinement**

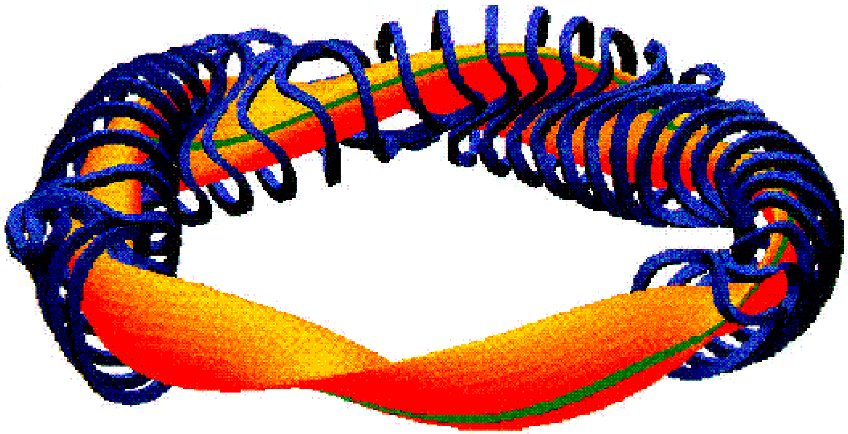
Through Advances in Theory, Computation, and Modeling a Better Understanding is Emerging

→ **A <u>Need</u> for New Experiments**

The World Stellarator Program is Substantial



Large Helical Device (Japan)
Enhanced confinement, high β;
A = 6-7, R=3.9 m, B=3$\rightarrow$4T



Wendelstein 7-X (Germany) (2008)
non-symmetric optimized design:
no current, A = 11, R=5.4 m, B=3T

- **New large international experiments use superconducting coils for steady-state**
- **Medium-scale experiments (W7-AS, CHS), and**
- **Exploratory helical-axis experiments in Japan, Spain, Australia.**

Large aspect ratios; physics-optimized designs without symmetry, no current.

Project to Large Reactors

Opportunity to Explore Low Aspect Ratio with Improved Neoclassical Transport *with* Plasma Current

- **Quasi-symmetry ⇒ symmetry of |B|**
  - **gives neoclassical transport analogous to (or better than!) the tokamak**
  - **has direction of low parallel viscous damping for E_r shear stabilization of turbulence**
  - **E_r shear without external momentum drive through proximity of electron/ion roots (W7-AS and CHS)**

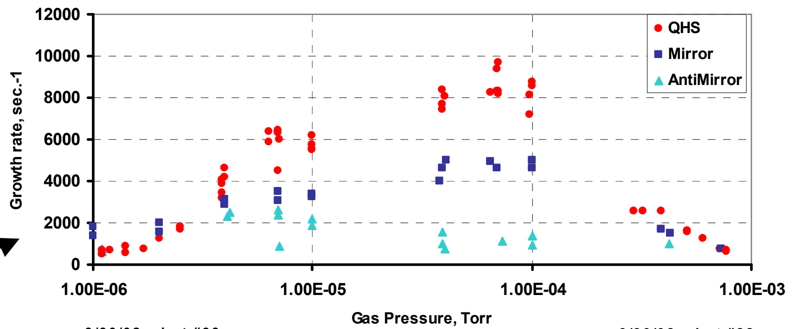
- **Improved 3-D codes are capable of finding attractive physics configurations, with quasi-symmetry and good flux surfaces, at low aspect ratio**

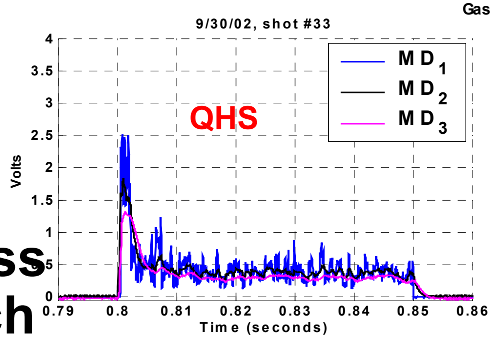
- **Research outside the US is not addressing benefits of quasi-symmetry**

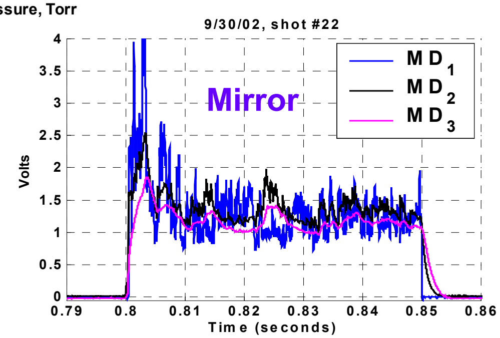
The US compact stellarator program elements include symmetry of |B| in the toroidal (NCSX), helical (HSX), and poloidal directions (QPS)

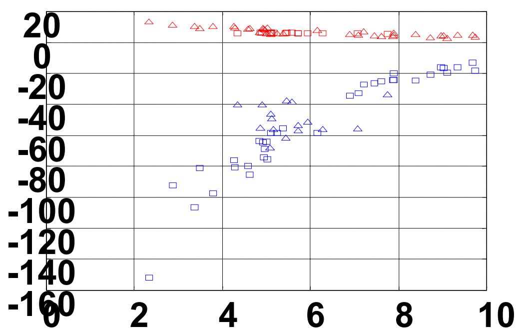
HSX Is Demonstrating Symmetry Matters!

- Demonstrated reduced direct losses in presence of quasi-symmetry
  - More rapid plasma build-up
  - Increased microwave absorption
  - Reduction of direct loss particles at ECH launch mirror to collector plates



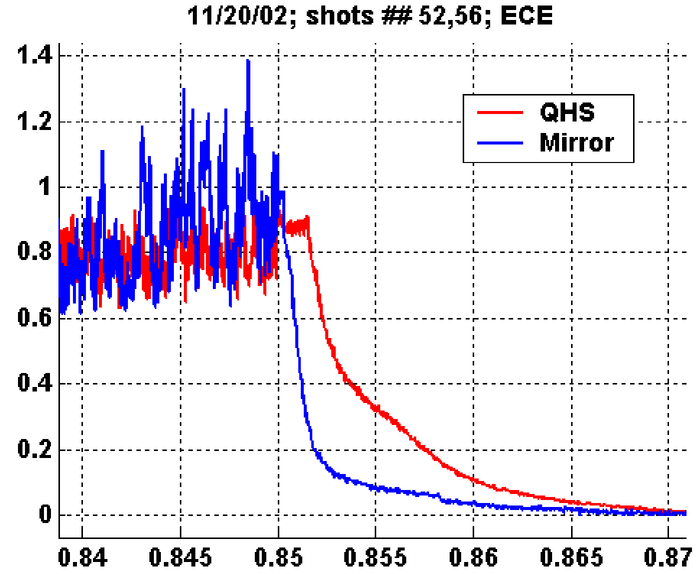




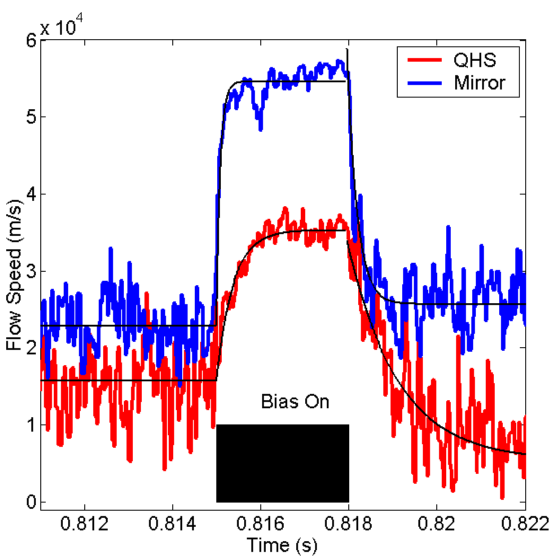


QHS Gives Improved Confinement of Suprathermals and Reduced Flow Damping

- ECE signal shows factor of ~3 longer decay for QHS over mirror-mode after ECH terminated.



•Factor ~3 in rise/fall times between QHS and Mirror in response to biased electrode, in good agreement with neoclassical theory.



Mirror (12 A)

$\tau \sim 0.15$ ms

QHS (5.7A)

$\tau \sim 0.4$ ms

The Goals of the Compact Stellarator Program

Evaluate the benefits and implications of the three forms of quasi-symmetry; stimulate and provide focus for 3-D theory and modeling for application to basic physics and toroidal confinement

=> The Real World is 3-D

A steady-state toroidal system at low aspect ratio with:

- **No disruptions**
- **Good neoclassical confinement; potential for flow control, ITB's**
- **High β limits**
- **No near-plasma conducting structures or active feedback control of instabilities**
- **No current or rotation drive ($\Rightarrow$ minimal recirculating power in a reactor)**

Directly Addresses FESAC 10-year Goal to "Assess Attractiveness of Compact Stellarator"

Likely Compact Stellarator Features

- **Rotational transform from bootstrap and externally-generated currents: (How much of each? Needed profiles? Consistency?)**
- **3D plasma shaping to stabilize limiting instabilities (How strong? What sets the limits?)**
- **Quasi-symmetric to reduce helical ripple transport, energetic particle losses, flow damping (How low must ripple be? Other flow drive mechanisms?)**
- **Power and particle exhaust via a divertor (What topology?)**
- **$R/\langle a \rangle \sim 4$ (How low?) and $\beta \sim 4\%$ (How high?)**

The US Stellarator Community has Mapped out a Balanced Program to Capitalize on Advances in Stellarators Not Covered in International Program

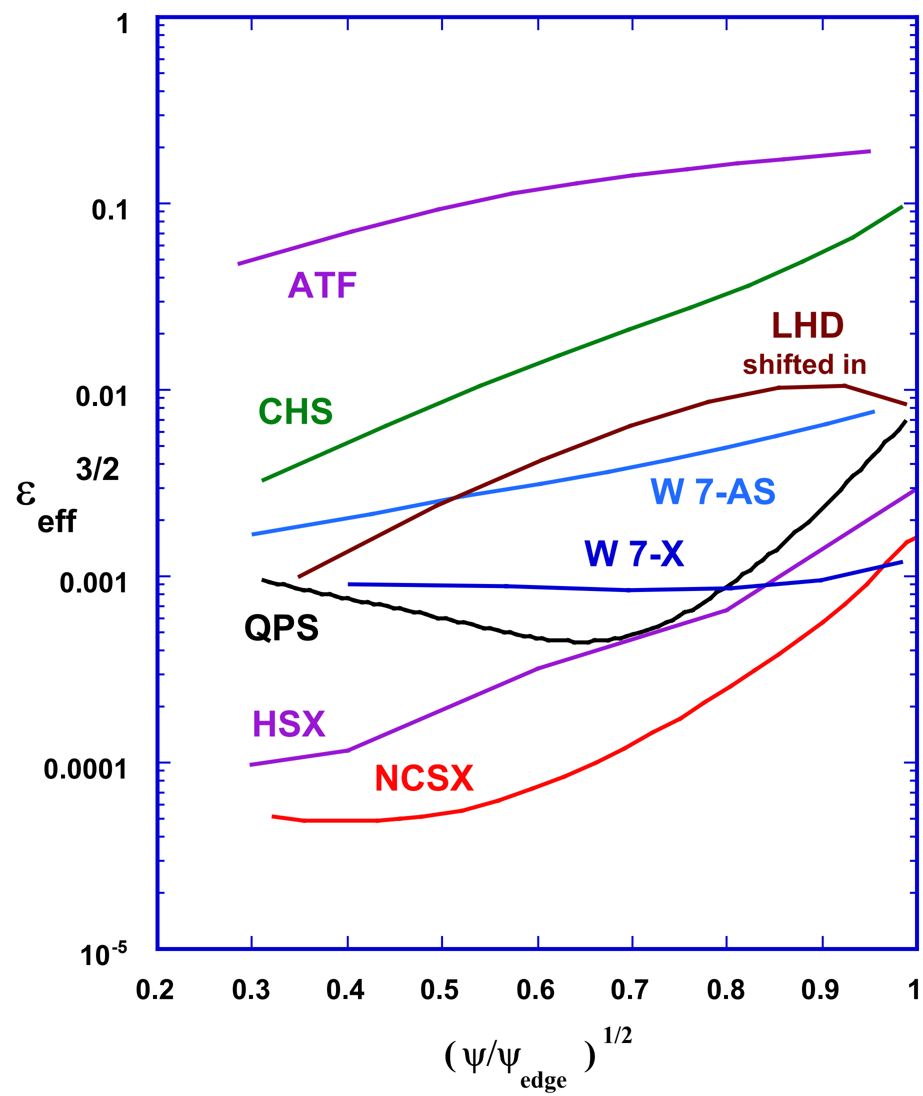
- CE Experiments, Existing and Under Construction
  - HSX - Quasi-helical symmetry, low collisionality electron transport
  - CTH - Kink and tearing stability, test of 3-D equilibrium measurement
- New Projects: NCSX, QPS
  - NCSX – Low collisionality transport, high beta stability, quasi-axisymmetry, low R/a – Integrated facility (main PoP Element)
  - QPS - Quasi-poloidal symmetry at very low R/a; complement NCSX
- Theory
  - Confinement, Stability, Edge, Energetic Particles, Integrated Modeling – Strong coupling to experimental program!
- International Collaboration
  - LHD, CHS, W7-AS $\Rightarrow$ W7-X, Theory
- ARIES Reactor Studies
  - Identify critical issues for CS reactors

Focus on Quasi-symmetries and Plasma Current

New Quasi-symmetric Stellarators have Low Neoclassical Transport – Examine Effects of I_p

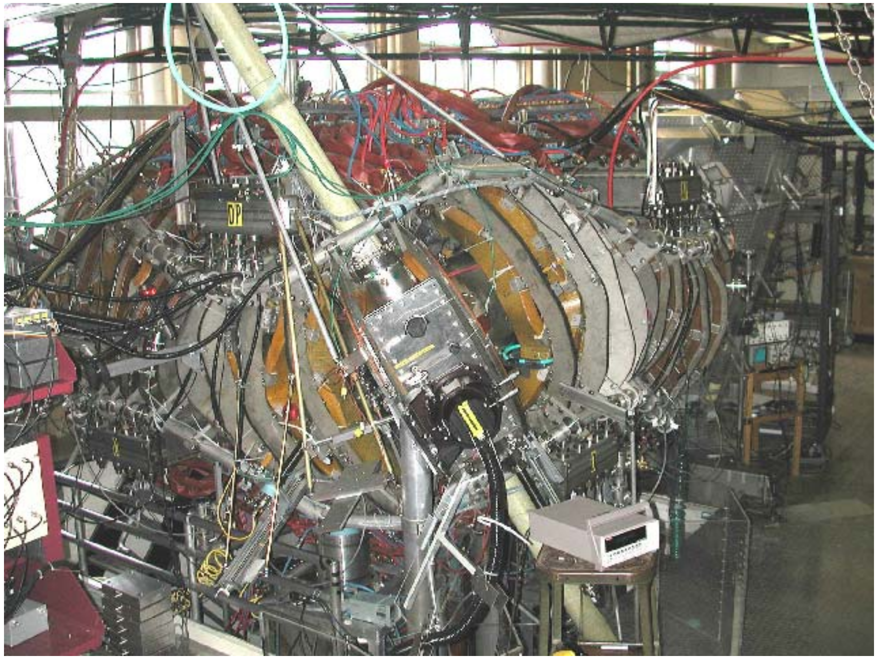
- In $1/\nu$ regime, asymmetrical neoclassical transport scales as $\varepsilon_{eff}^{3/2}$
- Low flow-damping
  - manipulation of flows for flow-shear stabilization
  - zonal flows like tokamaks
- Initial (successful!) test in HSX, studies continuing.
- Stability with finite current also a key issue for PoP program:

  CTH focused on kink & tearing stability with external transform.
- Low ν_*, high β test of quasi-axi - symmetry and current in NCSX.
- Very low R/a test of quasi -poloidal symmetry and current in QPS.



HSX Explores Improved Neoclassical Transport with Quasi-helical Symmetry

Worlds First Test of Quasisymmetry



R=1.2m, <a>=0.15m B = 1.0 T
4 periods, ECH 28GHz 200 kW
(additional 350 kW at 53 GHz in progress)
University of Wisconsin-Madison

- Test reduction of direct loss orbits and electron thermal conductivity.
- Demonstrate lower parallel viscous damping of plasma flows.
- Explore possible E_r control through plasma flow and/or ambipolarity constraint.
- Investigate turbulence and anomalous transport.
- Test stability limits to Mercier and ballooning modes.

Compact Toroidal Hybrid (CTH)

Auburn University

ISSUES:

How do we measure 3-D magnetic equilibrium of current-driven, finite-β stellarator?

- critical for equilibrium control & stability analysis of compact stellarators(NCSX & QPS)
  - $\Rightarrow$ CTH participating in ORNL/GA/Auburn V3FIT collaboration to test new 3-D reconstruction technique.
  - $\Rightarrow$ Measurement of internal rotational transform by novel MSE/LIF technique for improved equilibrium reconstruction.

Under what conditions are disruptions and other instabilities suppressed by 3-D helical field?

- Variable vacuum rotational transform & shape for broad investigation of disruption immunity

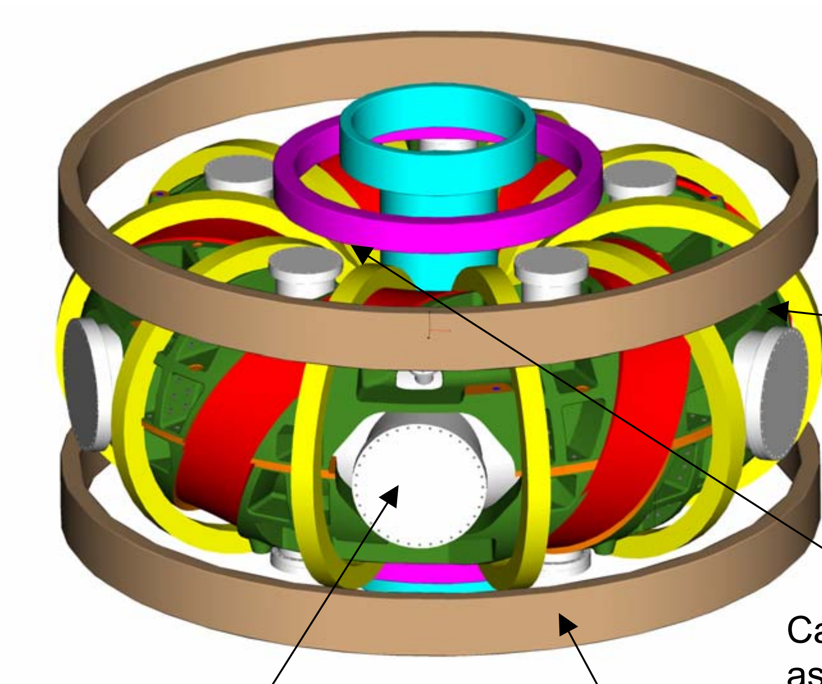
How do magnetic stochasticity & islands influence stability?

- External control of magnetic errors provided for.
- Measurement of static islands in plasma.

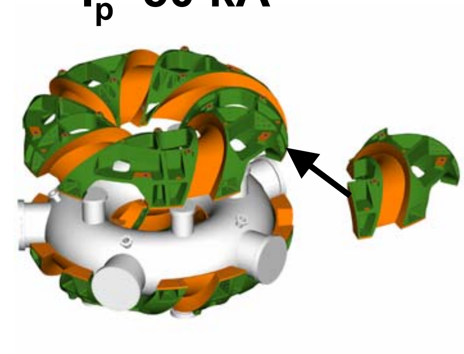
CTH device strongly contributes to key goals of US Compact Stellarator Program

- Active collaborations & linkages with other stellarator experiments & V3FIT development.

CTH assembly well underway
Operational late CY 2003



R = 0.75 m B=0.5T,
$\langle a \rangle$ = 0.2 m I_p=50 kA

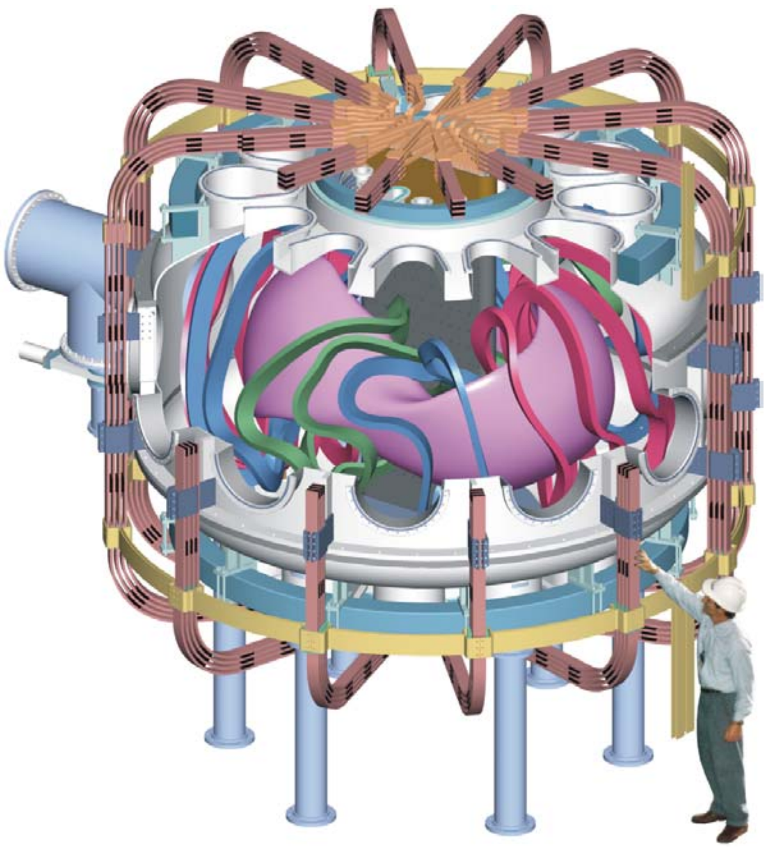


Cast & machined aluminum helical coil frame designed with assistance from PPPL; experience feeds into NCSX & QPS design. Prototype shown under construction.

Inconel vacuum vessel designed with assistance from PPPL; delivered 9/2002. Heaters & blankets being affixed.

Poloidal coils wound & potted on-site, completed 3/2003
Magnet fabrication experience from HSX

THE QUASI-POLOIDAL STELLARATOR (QPS)



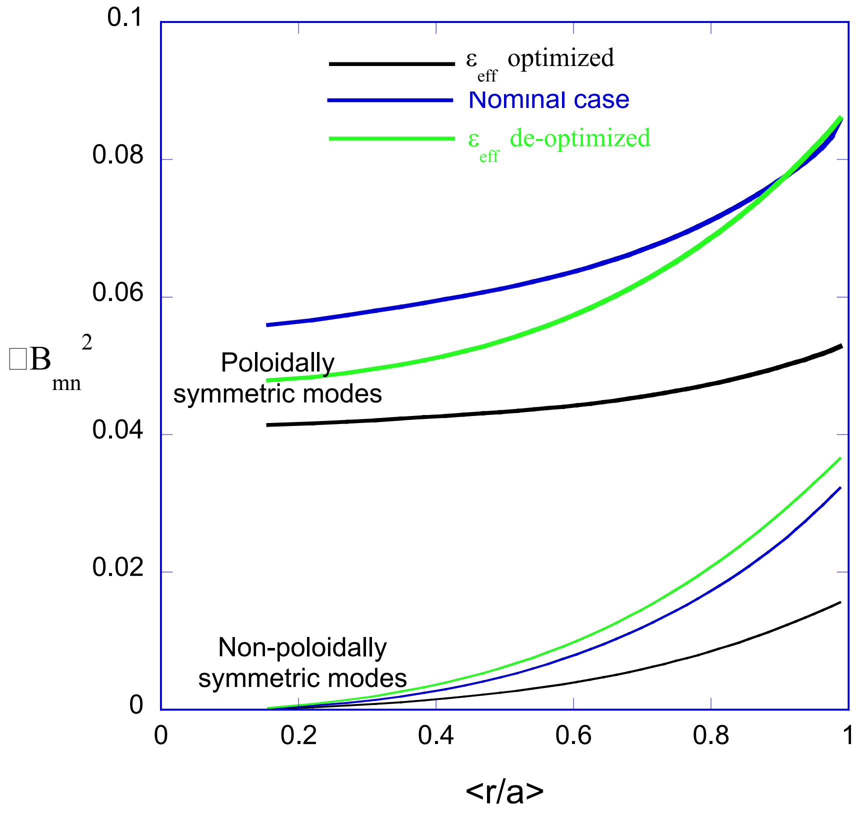
- $\langle R_{plasma} \rangle$ = 0.9-1 m
- $\langle a_{plasma} \rangle$ = 0.3-0.4 m
- V_{plasma} = 2-3 m^3
- R/a > 2.3
- B_{mod} = 1 ± 0.2 T
  for 1.5-s flat top
- P = 2-4 MW

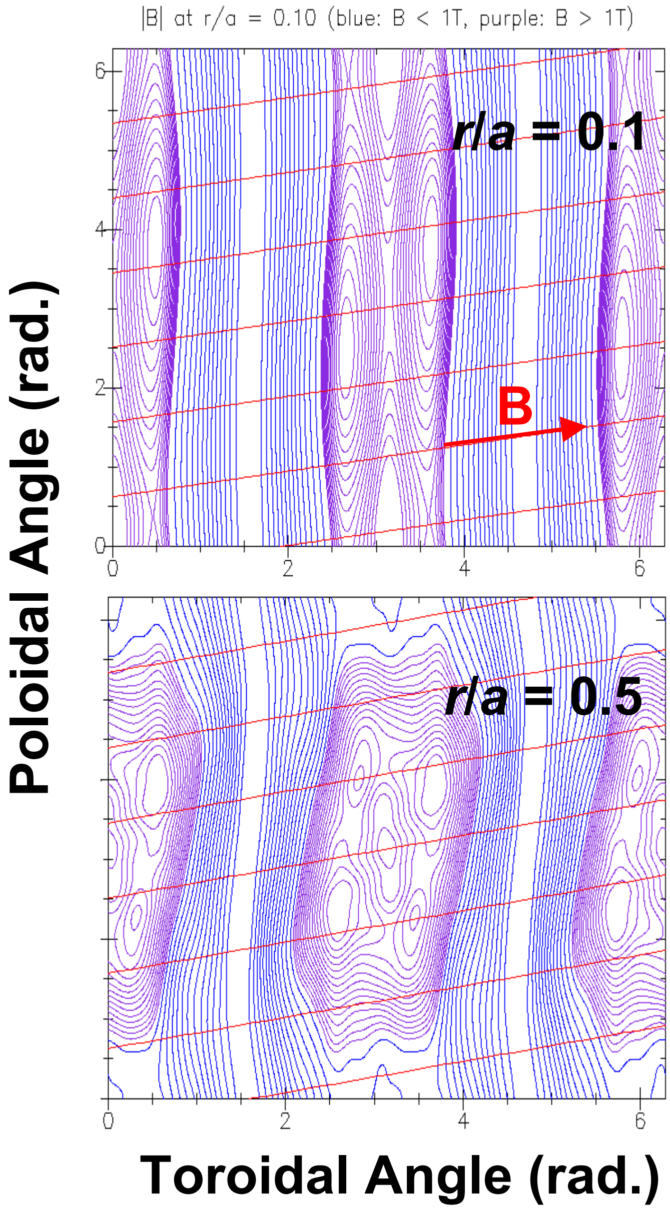
QPS is a CE-level experiment to study the physics of quasi-poloidal symmetry at very low aspect ratio

Status: successful Physics Validation Review, DOE Mission Need, CD-0 approval; Conceptual Design Review in August

Quasi-Poloidal Symmetry

- **The dominant components of the |B| Fourier series are poloidally symmetric in flux coordinates**

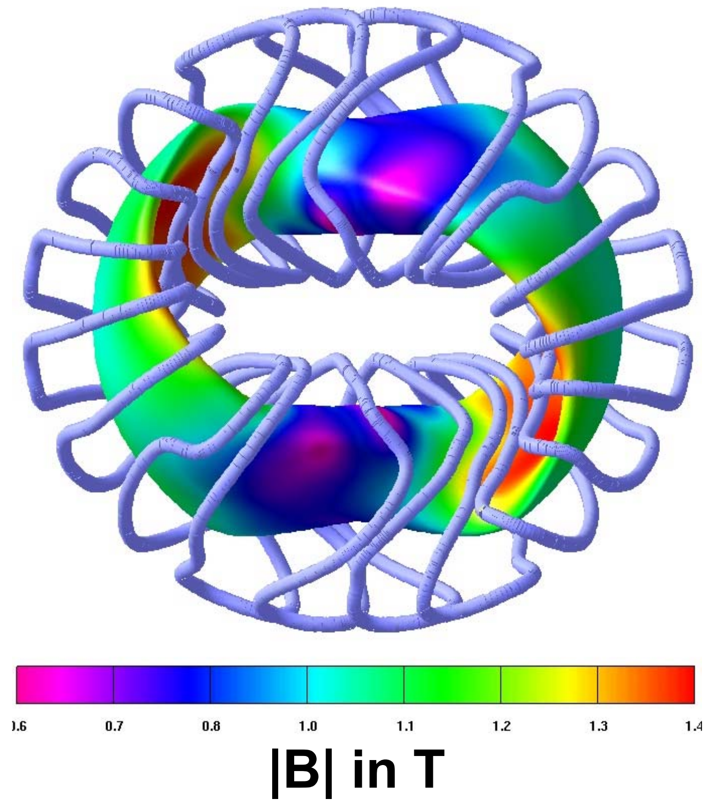




- **Reduces neoclassical transport, poloidal flow damping, bootstrap current, sensitivity to β, second stability threshold**

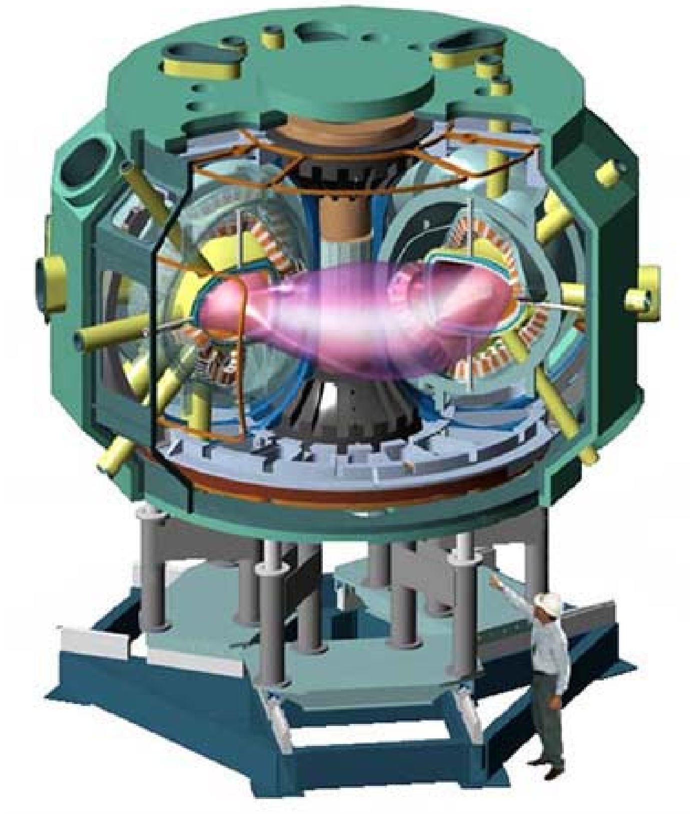
QPS Extends Stellarator/Toroidal Physics to Very Low *R*/*a* and Quasi-Poloidal Symmetry

- Anomalous transport, internal transport barriers, and flow shear
- Reduction of neoclassical transport
- Impact of poloidal flows on enhanced confinement
- Flux surface robustness at R/a>2.3 and β up to 2-3 % with strong toroidal/helical coupling
- Ballooning β character and MHD stability limits
- Benchmarking and improvement of 3-D theory



Complements NCSX in ten-year FESAC goal to determine the attractiveness of a Compact Stellarator; truly compact R/a <2.5

NCSX Mission: Addresses Integrated Issues of the Compact Stellarator



R=1.42m <a>=0.33m

B > 2 T (1.7 T at full ι_{ext}) P_{NBI} 3 => 6 MW

Macroscopic Stability:

- Disruptions - when, why, why not?
- High β, 3-D stability of kink, ballooning, neoclassical tearing, vertical displacement.

$\Rightarrow$ High heating power

Microturbulence and Transport:

- Is quasi-symmetry effective at high T_i?
- Challenge E_r shear understanding via ripple control.
  $\Rightarrow$ High T_i, flexible coil system

Wave-particle Interactions:

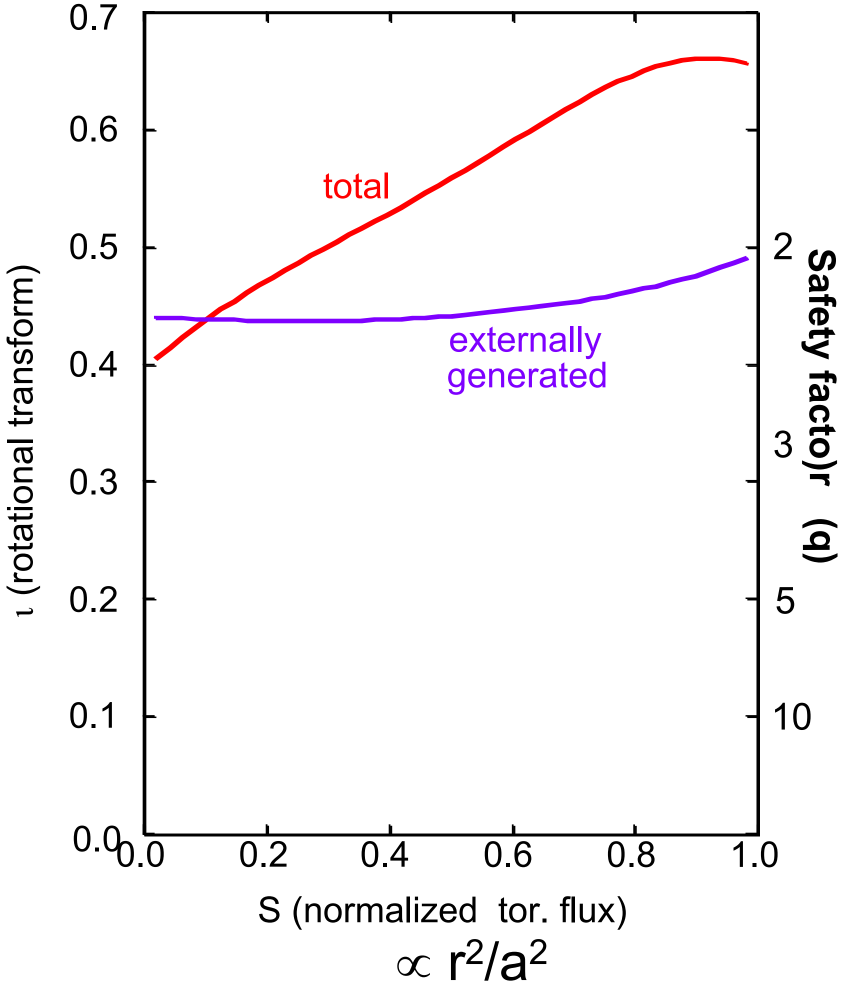
- Do we understand 3-D fast ion resonant modes & Alfvenic modes in 3-D?
  $\Rightarrow$ Good fast ion confinement

Plasma-boundary interaction:

- Effects of edge magnetic stochasticity?
  $\Rightarrow$ High power, flexible coil system

Quasi-axisymmetric Design to Build upon Tokamak and Stellarator Physics

Hybrid Configuration Combines Externally-Generated Fields with Bootstrap Current

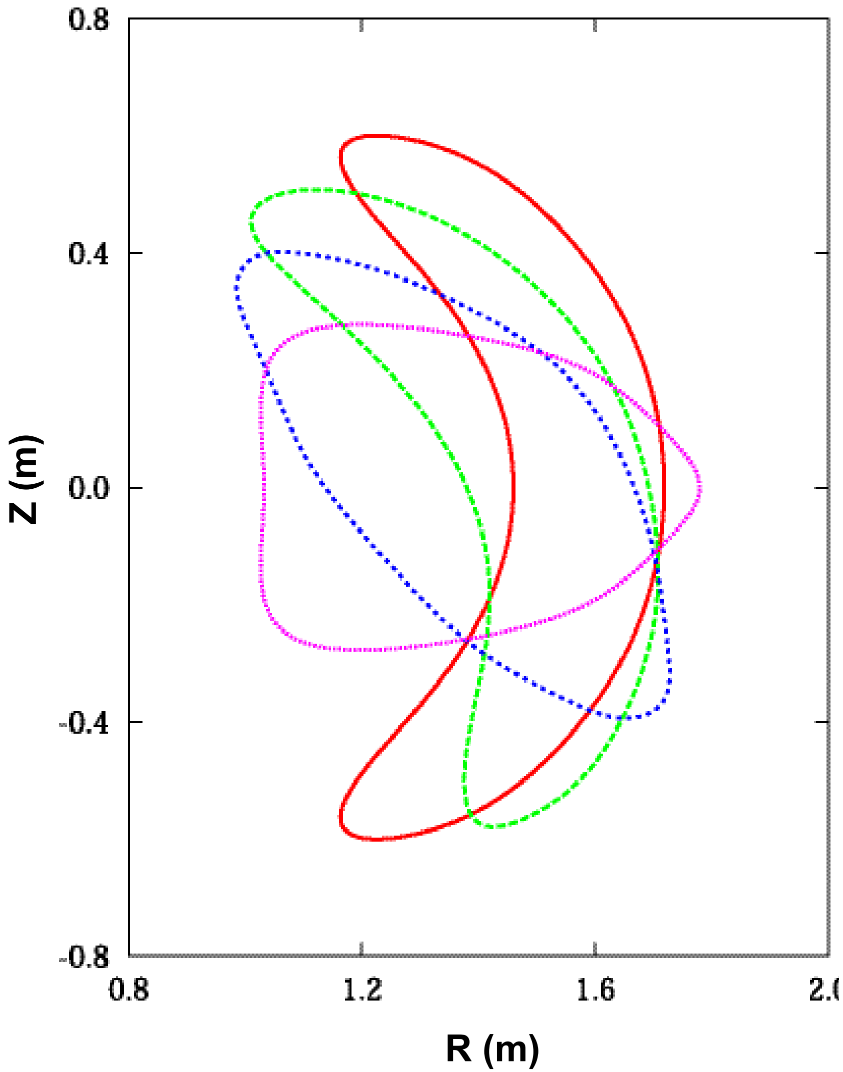


- **Assumed moderately broad pressure profile and consistent bootstrap current profile.**
- **~3/4 of transform (poloidal-B) from external coils.**
- **~1/4 of transform from bootstrap current (I_P = 174 kA with B=1.7 T at R=1.4m).**
- **'Reversed shear' stabilizes neoclassical tearing modes. Reduces turbulence drive.**

NCSX Target Equilibrium Has Attractive Properties

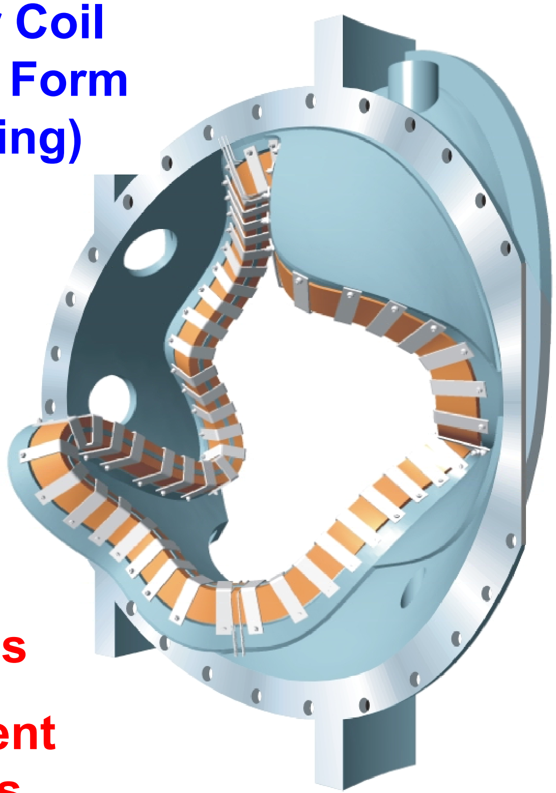
- 3 periods, low R/⟨a⟩ (4.4).
- Quasi-axisymmetric w/ low ripple.
  - $\varepsilon_{h,eff}$ = 0.1% in core, 2% at edge.
- Stable at β=4.1% to ballooning, kink, vertical, Mercier modes, w/out conducting walls or feedback.
- “Reversed shear” iota profile (0.39–0.65).
  - stabilize neoclassical tearing modes.
- Good magnetic surfaces; wide range of flexibility with coil current adjustment

Plasma Cross Sections



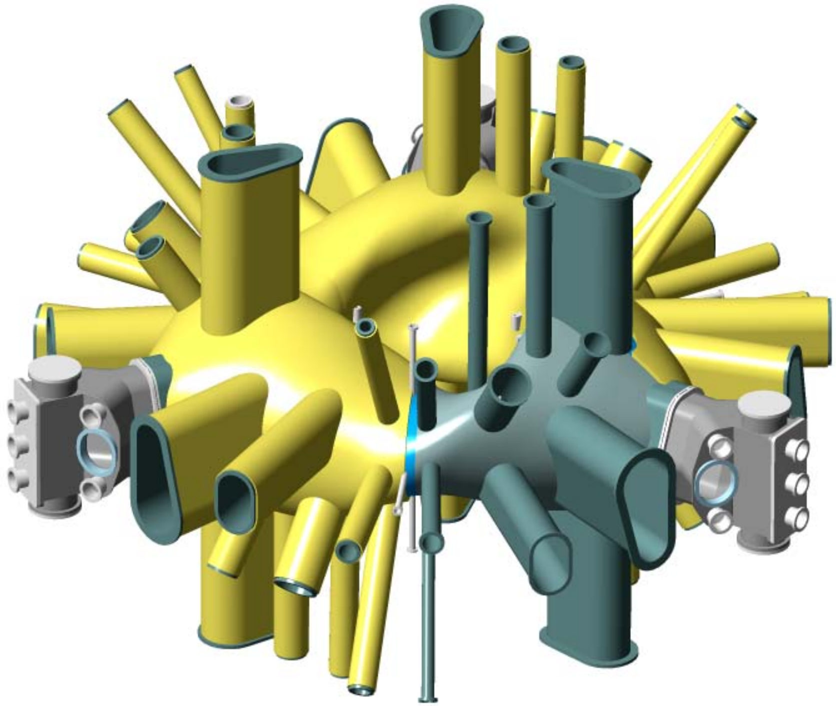
The Modular Coils and Vacuum Vessel are the Most Critical Components

Modular Coil
(Winding Form
+ Winding)



18 coils

3 different shapes



Vacuum Vessel
(shown with insulation)

- Winding forms and vacuum vessel are being built by industry.
- Coil winding and assembly will be done by PPPL.

On track for 1st plasma in FY07

Theory Is Critical to Advancing the Stellarator Concept

- Provides strong connection with world-wide program in both basic physics and fusion science
- US has a leadership role in worldwide 3-D theory and modeling
- World-wide efforts have drawn heavily on these tools in developing stellarator optimization
  - Theory has led experiment design (W7-X, HSX; Now NCSX, QPS)
  - Optimization should continue to look to future

A strong stellarator theory effort is required for the CS PoP Program

The Compact Stellarator Program Will Stimulate Development and Connections to Basic 3-D Plasma Physics

- **Most plasma problems are three-dimensional**
  - Magnetosphere; astrophysical plasmas
  - free-electron lasers; accelerators
  - perturbed axisymmetric laboratory configurations

- **Development of 3D plasma physics is synergistic, with stellarator research often driving new 3D methods.**
  - methods to reduce orbit chaos in accelerators based on stellarator methods
  - chaotic orbits in the magnetotail analyzed using methods developed for transitioning orbits in stellarators
  - astrophysical electron orbits using drift Hamiltonian techniques and magnetic coordinates developed for stellarators
  - tokamak and RFP resistive wall modes are 3D equilibrium issues
  - transport due to symmetry breaking was developed with stellarators

Key Theory Issues Which Need to be Addressed in CS PoP Program:

- Understand from first principles MHD β limits, transport, islation and stochasticity as applied to 3-D magnetic fields
- Understand microturbulence in 3-D versus 2-D systems
- Modeling power and particle handling in non-symmetric edges/divertors; edge field structure
- Explore role of energetic particles in MHD stability in a 3-D system
- Develop method to compare experimental and computational 3-D MHD equilibria

3-D Equilibrium Reconstruction is Needed for Understanding 3-D Plasma Behavior

A national working group is developing a 3D reconstruction code, starting with the evaluation of magnetic diagnostics in 3-D systems:

V3FIT group: S. P. Hirshman and E. A. Lazarus (Oak Ridge National Laboratory), L. L. Lao (General Atomics), J. D. Hanson and S. F. Knowlton (Auburn University)

New codes for rapidly computing magnetic sensor signals in 3-D plasmas have been written and tested:

- **Benchmarked against EFIT for DIII-D plasmas**
- **Being used to design magnetic diagnostics for NCSX and CTH**
- **Collaboration underway to test/compare results on CHS (NIFS) and W7AS**

The V3FIT Stellarator Equilibrium Reconstruction Code Will Be Built By Extending the Efficient EFIT Response Function Approach to 3-D

OAK RIDGE NATIONAL LABORATORY

UT-BATTELLE

AUBURN UNIVERSITY

US Program Benefits from International Collaborations

- **Cooperation on the development of the HSX, NCSX and QPS designs and computational tools(Australia, Austria, Germany, Japan, Russia, Spain, Switzerland, Ukraine)**

- **Participation in ongoing experiments**
  - **Fast ion and neutral particle diagnostics on LHD and CHS, high β on W7AS**
  - **Pellet injection, ICRF heating, bolometry and magnetic diagnostics on LHD**
  - **Collaborations with TJ-K and H-1 on turbulence studies in HSX**

- **Joint theory/code work to understand basic science of 3-D system and promote better understanding of experiments**
  - **Microinstabilities (FULL), nonlinear GK (GS-2 & GTC under 3-D development)**
  - **3-D MHD without assumed flux surfaces (PIES and HINT); 3-D equilibrium reconstruction – code development, application & benchmarking (W7AS, LHD, and CHS)**

- **Benefit from access to PE level experiments and their physics/technology results.**

Reactor Studies

- Stellarator Power Plant Study (SPPS-'scoping study') carried out by the ARIES Team (1997) concluded the MHH4-based power plant was economically competitive with the 2nd stability ARIES-IV tokamak
- Recent assessment of low-R/a QA and QP configurations as reactors (IAEA 2000) used same assumptions as for other stellarator reactors, resulting in smaller size, higher wall loading; QA 8.8m, QP 7.3m
- Design issues for quasi-symmetric configurations as applied to reactors are being evaluated in ongoing ARIES study.

Strong Theory and Experiment

System Studies

Identification of Reactor Improvements

What Do We Expect to Learn from the CS Program?

- What are the conditions for disruption immunity?
- Develop an understanding of β stability limits in 3-D for pressure and current driven modes.
  - True understanding between theory, codes and experiment
- How can anomalous transport be controlled in stellarators?
  - flow shear and/or adjacent location of electron and ion roots for E_r?
- What level of symmetry is needed/acceptable to
  - 1) ensure energetic particle confinement,
  - 2) keep neoclassical losses less than anomalous, and
  - 3) keep flow damping low?
- What are the benefits of high effective transform (low-q)?
- How robust can configurations at low aspect ratio be to finite pressure, field errors and plasma current?
- How to diagnose and reconstruct 3-D equilibria (V3FIT)
- Is a PE experiment advisable based upon what we learn in the Compact Stellarator Program? If so, what is the best approach?

Concluding Remarks

- **Balanced program focused on the 10-Year IPPA Goal:**

  "Determine Attractiveness of Compact Stellarator"
- **Has a strong science element**
  - *Benefits of quasi-symmetry*
  - *Advantages and limitations of plasma current in 3-D systems*
  - *Real plasmas are 3-D*
- **Set of UNIQUE devices in world-wide program**
  - **HSX:QHS, very low neoclassical transport with high ι_{eff}, reduced flow damping, anomalous transport, pressure-driven instability**
  - **CTH: Current-driven instabilities at low aspect ratio, detailed equilibrium/current measurements, disruption limits**
  - **NCSX: Integrated PoP test of compact stellarator; connects to and complements the AT**
  - **QPS: Very low aspect ratio test of quasi-poloidal symmetry**
- **The Compact Stellarator Program is an exciting opportunity for unique fusion science.**
  - **Stabilize high-β instabilities with 3D shaping; understand 3D effects**
  - **Reduced transport in low-collisionality 3-D systems**

- **Strong linkages with all of magnetic fusion science, with theory playing a central role.**
    - **Integrates well scientifically with international program**

- **Physics basis is sound, attractive configurations identified**
    - **Building upon large international stellarator and tokamak programs**

- **Compact Stellarators provide innovative solutions to make magnetic fusion more attractive.**
    - **Combine best characteristics of stellarators and tokamaks.**
    - **Potentially eliminate disruptions; intrinsically steady state**

Tremendous opportunity to expand our scientific understanding of 3-D systems and identify potential reactor improvements using 3-D Shaping